A New Spreading Scheme for Convolutionally Coded CDMA Communication in a Rayleigh-Fading Channel

Young Jo Bang and Sang Wu Kim

Abstract— **We find that the asymptotic bit-error probability (BEP), P_b, of a convolutionally coded code-division multiple-access (CDMA) system in a frequency-selective Rayleigh-fading channel depends on the length of the shortest error event path and the product of symbol distances (to be defined later) along that path. Based on this observation, we propose a new spreading scheme that maximizes the length of the shortest error event path. It is shown that the proposed scheme yields an improvement of 1.0–1.3 dB at $P_b = 10^{-5}$ over the conventional convolutionally coded CDMA system, and even a higher improvement can be achieved as the required BEP is decreased.**

I. Introduction

RECENTLY, there has been increased interest in the use of direct-sequence code-division multiple-access (DS/CDMA) for wireless communication systems. DS/CDMA has the advantages of inherent diversity to multipath and increased user capacity [1]. In DS/CDMA systems, an error correcting code is virtually always employed to obtain acceptable performance, because the multiple access interference causes the transmitted signal to be received erroneously. In particular, convolutional (or trellis) codes with Viterbi decoding have been extensively applied to DS/CDMA systems [2]–[5].

Recent conspicuous studies for convolutionally (or trellis) coded CDMA systems have been accomplished by Boudreau [4], Woerner [5], and Miller [6]. Boudreau has proposed a system model that allows one to apply both trellis codes employing an M-ary phase shift keying (MPSK) signal constellation and a pseudo noise (PN) spreading sequence to the data symbols to be transmitted. He has compared the performances of trellis coded and convolutionally coded DS/CDMA schemes, and has shown that the latter outperforms the former in both additive white Gaussian noise (AWGN) and Rician fading channel. On the other hand, Woerner has proposed a trellis coded scheme that is constructed over a biorthogonal set of spreading sequences, and has shown that the proposed scheme outperforms the convolutionally coded scheme in AWGN channel. Miller has considered the design of rate $1/n$ trellis codes with M-ary ($M = 2^n$) orthogonal signal constellations and analized their performance by using a transfer function. In these analyzes, however, they used the standard convolutional codes that have been optimally designed for AWGN channels (i.e., optimal in the sense of maximal Hamming free distance), and made no attempt to optimize the spreading scheme in fading channel.

In this paper, we present a simple expression for the asymptotic bit-error probability (BEP) of the convolutionally coded CDMA (CC-CDMA) system in a frequency-selective Rayleigh-fading channel, assuming that an ideal interleaving is used. Furthermore, we assume that the coherent RAKE receiver is used and that the receiver is capable of perfect carrier recovery (coherent reception), acquisition, and tracking. Coherent reception can be accomplished by using a pilot signal. This technique is adopted on the forward link of the IS-95 standard and on both forward and reverse links of broadband CDMA system [7]. Under these assumptions, we show that the asymptotic BEP depends on two factors: the length of the shortest error event path and the product of symbol distances (to be defined later) along that path. Based on this observation, we propose a new spreading scheme for CC-CDMA communication which maximizes the length of the shortest error event path. It is found that this scheme is also optimal for the AWGN channel, because it maximizes the free distance.

II. System and Channel Model

We assume that there are K active transmitters, each employing a set of M spreading sequences of length N that spans one code symbol. For transmitter j, each interleaved code symbol is added modulo-2 with one of the M spreading sequences $\{\mathbf{c}_1^j, \mathbf{c}_2^j, \cdots, \mathbf{c}_M^j\}$, and then multiplied by a carrier (BPSK modulated) as shown in Fig. 1. The spreading sequence being added is determined by the code symbols. With conventional CC-CDMA [5] M is one. We will show in Section IV that a performance improvement can be made by using more than one spreading sequence.

We assume each transmitted signal experiences a frequency-selective Rayleigh fading and a delay of $\tau^j, j = 1, 2, \cdots, K$. The following assumptions are made regarding the characteristics of the fading channel: 1) channel response is due to wide-sense-stationary uncorrelated-scattering (WSSUS); 2)

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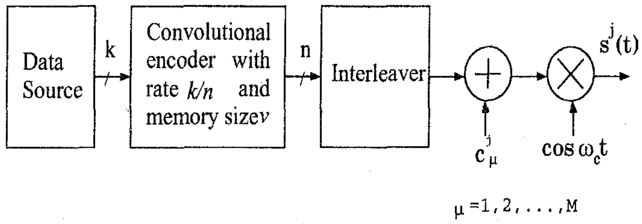

Fig. 1. The transmitter model for user j.

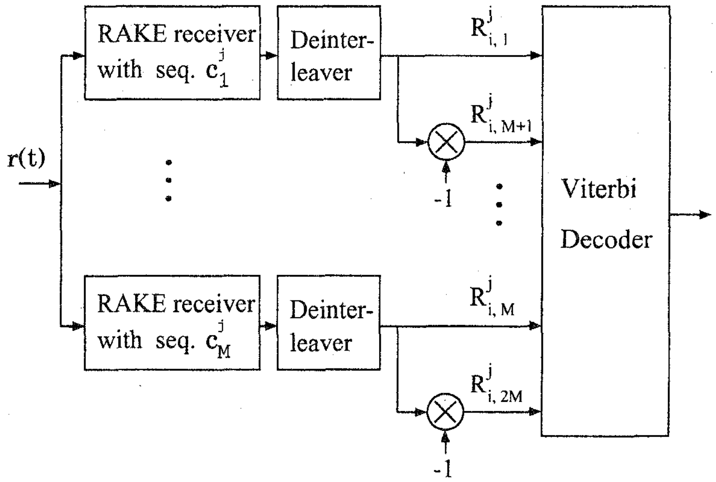

Fig. 2. The receiver model for detecting the signal of transmitter j.

multipath delay spread T_m, defined as the range of time over which the average power of the channel output is essentially nonzero, satisfies $T_m > T_c$, where T_c is the chip duration; 3) coherence time of the channel is sufficiently slow so that the channel response $h(\tau; t)$ remains constant over several bits and can be measured by the receiver. The low-pass equivalent impulse response $h^j(\tau; t)$ of the fading channel at time t for transmitter j is commonly modeled by a truncated tapped delay line with a tap spacing of T_c [8]

$$h^j(\tau; t) = \sum_{l=0}^{L_D-1} \beta^j_{l,i} \delta(\tau - lT_c) \exp(j\theta^j_{l,i}) \qquad \forall t \in [(i-1)T, iT] \tag{1}$$

where T is the duration of a code symbol, and $\beta^j_{l,i}$ and $\theta^j_{l,i}$ are the tap gain and the phase associated with a path of delay lT_c, respectively. We assume that the tap gains are independent Rayleigh random variables, and the tap phases are independent and uniformly distributed over $[0, 2\pi]$. The number of resolvable multipath components, L_D, is given by

$$L_D = \lfloor T_m/T_c \rfloor + 1. \tag{2}$$

We assume that the signal-to-noise ratios (SNR's) of the different resolved paths decrease exponentially with increasing path delay, that is

$$E\left[(\beta^k_l)^2\right] \triangleq \sigma^2_l = \sigma^2_0 \exp[-l/\eta] \qquad 1 \le l \le L_D - 1,\ 1 \le k \le K \tag{3}$$

where $\eta = (L_D - 1)/5$ [9].

Our receiver model, shown in Fig. 2, is similar to that of [5], except the use of a RAKE receiver instead of a correlator receiver, because we consider a frequency-selective Rayleigh-fading channel. We assume that each RAKE receiver has L_D taps and perfectly knows the fading amplitudes and phases of the multipaths by using a pilot signal [10]. In Fig. 2, $R^j_{i,\mu}$, for $1 \le \mu \le M$, is the output of RAKE receiver with sequence $\mathbf{c}^j_\mu$ and $R^j_{i,\mu+M}$, for $1 \le \mu \le M$, is the output of RAKE receiver with sequence $-\mathbf{c}^j_\mu$. Since $R^j_{i,\mu+M} = -R^j_{i,\mu}$, for $1 \le \mu \le M$, we do not need RAKE receivers for sequences $-\mathbf{c}^j_\mu$, $\mu \in \{1, 2, \cdots, M\}$. The Viterbi decoder selects the most probable path at time m, i.e., the path that maximizes $\sum_{i=1}^m R^j_{i,\mu}, \mu \in \{1, 2, \cdots, 2M\}$.

III. Performance Analysis

In this section, we analyze the BEP P_b of the CC-CDMA system in a frequency-selective Rayleigh-fading channel. An upper-bound on P_b can be obtained using the union bound [11]

$$P_b \le \frac{1}{k} \sum_{\tilde{\mathbf{p}} \in \tilde{\mathbf{C}}} W_{\mathbf{p},\tilde{\mathbf{p}}} P(\mathbf{p} \to \tilde{\mathbf{p}}), \quad \forall \mathbf{p} \tag{4}$$

where k is the number of information bits per trellis branch, $\tilde{\mathbf{C}}$ is the set of error paths, $W_{\mathbf{p},\tilde{\mathbf{p}}}$ is the number of bit errors involved in choosing an incorrect path $\tilde{\mathbf{p}}$ instead of the correct path $\mathbf{p}$, and $P(\mathbf{p} \to \tilde{\mathbf{p}})$ is the probability of selecting an incorrect path $\tilde{\mathbf{p}}$ instead of the correct path $\mathbf{p}$.

Let $\tilde{\mathbf{p}}$ be the path which diverges from the correct path $\mathbf{p}$ and remerges after J branches. Then the Chernoff bound on pairwise error probability for transmitter j, conditioned on the fading amplitude and phase vector, denoted $\underline{\beta}^j$ and $\underline{\theta}^j$, respectively, is given by [10]

$$\begin{aligned} P(\mathbf{p} \to \tilde{\mathbf{p}} \mid \underline{\beta}^j, \underline{\theta}^j) &= P\left(\sum_{i=1}^{nJ} R^j_{i,p_i} < \sum_{i=1}^{nJ} R^j_{i,\tilde{p}_i} \mid \underline{\beta}^j, \underline{\theta}^j \right) \\ &\le \min_{\lambda > 0} \prod_{i=1}^{nJ} E(\exp[-\lambda D_{p_i,\tilde{p}_i}]) \end{aligned} \tag{5}$$

where n is the number of code bits per trellis branch and

$$D_{p_i,\tilde{p}_i} = \sum_{l=0}^{L_D-1} \left\{ \sqrt{\frac{E_s T}{2}} \left(\left(\beta^j_{l,i}\right)^2 \tilde{n}_i + \beta^j_{l,i} I_i \right) + \beta^j_{l,i} \xi_i \right\} \tag{6}$$

represents the decision statistics for the ith code symbol interval. In (6), E_s is the energy of a code symbol, $\tilde{n}_i$ is the number of nonzero pairwise distances between the spreading sequences along the correct path $\mathbf{p}$ and the incorrect path $\tilde{\mathbf{p}}$ for the ith code symbol divided by N. Notice that $\tilde{n}_i = 0$ if the two sequences are identical, $\tilde{n}_i = 1/2$ if they are orthogonal, $\tilde{n}_i = 1$ if they are antipodal. I_i is the multiple access interference (MAI) which is modeled by a Gaussian noise with zero mean and variance of $\sum_{l=0}^{L_D-1} \sigma_l^2 (K-1)\tilde{n}_i/(3N)$ [12], [13], and ξ_i is AWGN with zero mean and variance of $N_0 T \tilde{n}_i / 4$ [5].

By averaging (5) over β_l^j, we obtain the pairwise error probability $P(\mathbf{p} \to \tilde{\mathbf{p}})$

$$P(\mathbf{p} \to \tilde{\mathbf{p}}) \le \prod_{i \in \nu} \left\{ \prod_{l=0}^{L_D-1} \left(1 + \sigma_l^2 \gamma_s d_i^2\right) \right\}^{-1} \tag{7}$$

where

$$\gamma_s = \frac{1}{8} \left(\frac{N_0}{2E_s} + \sum_{l=0}^{L_D-1} \sigma_l^2 \frac{(K-1)}{3N} \right)^{-1}$$

$d_i^2 = 4\tilde{n}_i$ is defined as the symbol distance, and ν is the set of all $i (1 \le i \le nJ)$ for which $d_i^2 \neq 0$.

In order to gain insight on the system performance, we examine the asymptotic BEP. For high SNR (i.e., $\gamma_s \gg 1$), $1 + \sigma_l^2 \gamma_s d_i^2 \approx \sigma_l^2 \gamma_s d_i^2$, and the shortest (in length of error event) error event path would dominate the error performance. Thus, the BEP P_b is approximately given by

$$\begin{aligned} P_b &\approx \frac{1}{k} \cdot W_s \cdot \frac{\left[\prod_{l=0}^{L_D-1} \left(\sigma_l^2 \gamma_s\right) \right]^{-L}}{\left(\prod_{i \in \hat{\nu}} d_i^2\right)^{L_D}} \\ &= \frac{1}{k} \cdot W_s \cdot \frac{\left[\prod_{l=0}^{L_D-1} \left(\sigma_l^2 \gamma_s\right) \right]^{-L}}{\left(d_p^2\right)^{L_D}} \end{aligned} \tag{8}$$

where W_s is the number of bit errors along the shortest error event path, $\hat{\nu}$ is the set of all i for which $d_i^2 \neq 0$ along the shortest error event path, and L and d_p^2 are the length of the shortest error event path (defined as the number of elements in $\hat{\nu}$) and the product of symbol distances along that path, respectively. In view of (8), increasing both L and d_p^2 plays an important role in decreasing the BEP of the CC-CDMA system in the Rayleigh-fading channel. A similar observation has been made by Divsalar and Simon [14] for a trellis-coded narrowband system.

TABLE I
THE MAPPING RULE FOR EACH GROUP

b_{2i}	b_{2i+1}	pair of spreading sequences	
1	1	$\mathbf{c}_1$	$\mathbf{c}_1$
1	-1	$\mathbf{c}_2$	$-\mathbf{c}_2$
-1	1	$-\mathbf{c}_2$	$\mathbf{c}_2$
-1	-1	$-\mathbf{c}_1$	$-\mathbf{c}_1$

IV. PROPOSED CC-CDMA SYSTEM AND NUMERICAL RESULTS

The main idea of our proposed CC-CDMA scheme is to expand the size M of the spreading sequence set and thereby to maximize L. Clearly, the maximum of L is achieved if distinct spreading sequences are used for each trellis branch, and the maximum of L is nJ_s, where J_s is the number of branches of the error event path having the minimum number of branches. This would, however, require 2^{v+k} RAKE receivers, where v is the memory size of convolutional encoder. In this paper, we propose a new CC-CDMA (NCC-CDMA) scheme which maximizes L with $M = 2$, while d_p^2 is kept unchanged.

A sequence of n code symbols in each branch, $(b_0, b_1, \cdots, b_{n-1})$, is divided into $n/2$ groups, each consisting of two code symbols. We assume n is even. For transmitter j, we assign a pair of spreading sequences to each group as shown in Table I, where we have dropped the superscript j for the simplicity of notation. Then, this rule guarantees that the number of symbols having nonzero symbol distance (i.e., $d_i^2 \neq 0$) between any two groups is two.

Table II shows the generators that maximize L when this mapping rule is applied. Notice that the L obtained is equal to nJ_s, the maximal length of the shortest error event path. These generators are identical to those that maximize d_{free} [15], except the position of some generators. For example, for the convolutional code having rate $r = 1/4$ and memory size $v = 4$, the standard generators that maximize d_{free} are 25, 27, 33, 37 while the generators that maximize L and d_{free} are 25, 33, 27, 37. The reason for exchanging 27 and 33 is to avoid the case of $d_i^2 = 0$ and thereby to increase L. For example, suppose that the code symbols in a correct trellis branch and those in an incorrect trellis branch are 1111 and 11-1-1, respectively. Then after assigning a pair of spreading sequences as indicated in Table I, we will get $L = 2$ for this particular branch. However, L can be increased to 4 by exchanging the second and the third code symbol (by exchanging the corresponding generators), and thereby making the assigned spreading sequences to be $\mathbf{c}_1\mathbf{c}_1\mathbf{c}_1\mathbf{c}_1$ and $\mathbf{c}_2 {-\mathbf{c}_2} \mathbf{c}_2 {-\mathbf{c}_2}$, respectively. Notice that exchanging the position of code symbols does not change d_{free}. Here, one must be careful in exchanging the generators not to make the length of an error event with $J (> J_s)$ branches be less than nJ_s.

With our scheme, the product of symbol distances, d_p^2, along the shortest error event path is

$$\begin{aligned} d_p^2 &= \prod_{i \in \hat{\nu}} d_i^2 \\ &= [d(\mathbf{c}_l, -\mathbf{c}_l)]^a [d(\mathbf{c}_1, \mathbf{c}_2)]^b [d(\mathbf{c}_1, -\mathbf{c}_2)]^c, \ l = 1, 2, \end{aligned} \tag{9}$$

TABLE II
THE CONVOLUTIONAL CODES MAKING L MAXIMIZED

code rate(r)	memory size(v)	Generators in octal				J_s	L
$\frac{1}{2}$	2	5	7	-	-	3	6
	3	15	17	-	-	4	8
	4	23	35	-	-	5	10
	5	53	75	-	-	6	12
$\frac{1}{4}$	2	5	7	7	7	3	12
	3	13	15	15	17	4	16
	4	25	33	27	37	5	20
	5	53	75	71	67	6	24
$\frac{1}{8}$	2	7	5	7	5	3	24
		5	7	7	7		
	3	17	13	17	13	4	32
		13	15	15	17		
	4	37	25	33	25	5	40
		35	33	27	37		
	5	57	73	51	67	6	48
		75	47	65	57		

where a, b, and c are the number of elements in the set $\hat{\nu}$ with d_i^2 equal to $d(\mathbf{c}_l, -\mathbf{c}_l), d(\mathbf{c}_1, \mathbf{c}_2)$, and $d(\mathbf{c}_1, -\mathbf{c}_2)$, respectively, where $d(\mathbf{c}_1, \mathbf{c}_2)$ is the Hamming distance between $\mathbf{c}_1$ and $\mathbf{c}_2$ divided by $N/4$. Since $d(\mathbf{c}_1, -\mathbf{c}_2) = 4 - d(\mathbf{c}_1, \mathbf{c}_2), d(\mathbf{c}_l, -\mathbf{c}_l) = 4$, and $b = c$ (because a pair of spreading sequences is assigned to each group of two code symbols), d_p^2 is given by

$$d_p^2 = 4^a \cdot \{d(\mathbf{c}_1, \mathbf{c}_2)(4 - d(\mathbf{c}_1, \mathbf{c}_2))\}^b, \quad \text{where } a + 2b = L. \tag{10}$$

We can show from (10) that d_p^2 is maximized when $d(\mathbf{c}_1, \mathbf{c}_2) = 2$, i.e., $\mathbf{c}_1$ and $\mathbf{c}_2$ are orthogonal.

As an example, consider a rate $1/2$, four-state convolutional code with trellis diagram illustrated in Fig. 3(a). The trellis diagrams for conventional CC-CDMA (CCC-CDMA) and NCC-CDMA schemes are illustrated in Fig. 3(b) and (c). The asymptotic BEP P_b with CCC-CDMA scheme can be evaluated via (8) as

$$P_b \approx \frac{\left[\prod_{l=0}^{L_D-1} (\sigma_l^2 \gamma_s)\right]^{-5}}{(4 \cdot 4 \cdot 4 \cdot 4 \cdot 4)^{L_D}} = \frac{\left[\prod_{l=0}^{L_D-1} (\sigma_l^2 \gamma_s)\right]^{-5}}{(4^5)^{L_D}} \tag{11}$$

whereas the asymptotic P_b with NCC-CDMA scheme is

$$P_b \approx \frac{\left[\prod_{l=0}^{L_D-1} (\sigma_l^2 \gamma_s)\right]^{-6}}{(4 \cdot 4 \cdot 2 \cdot 2 \cdot 4 \cdot 4)^{L_D}} = \frac{\left[\prod_{l=0}^{L_D-1} (\sigma_l^2 \gamma_s)\right]^{-6}}{(4^5)^{L_D}}. \tag{12}$$

Notice that d_p^2 are the same (i.e., 4^5) for both schemes, but L is six with NCC-CDMA whereas L is five with CCC-CDMA.

Table III shows that the NCC-CDMA scheme yields a larger L than the CCC-CDMA does, while d_p^2's are identical for both schemes. This indicates that, for high SNR, NCC-CDMA scheme yields a lower BEP than CCC-CDMA scheme does. Furthermore, the free distance $d_{\text{free}}^2 \triangleq \min_\nu \left(\sum_{i \in \nu} d_i^2\right)$ with NCC-CDMA is equal to that with CCC-CDMA which is designed to yield the maximal free distance, and thus the proposed scheme is also optimal for AWGN channel.

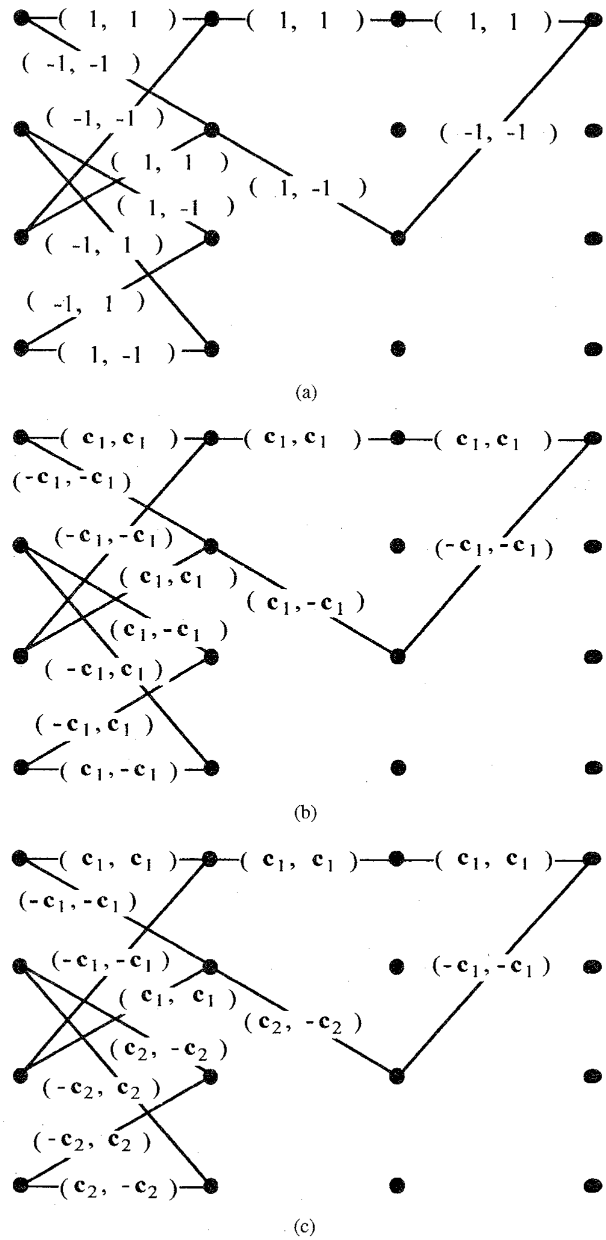

Fig. 3. Trellis diagram for rate 1/2 codes with four-state: (a) convolutional code, (b) CCC-CDMA scheme, and (c) NCC-CDMA scheme.

In order to verify the validity of the results, we have performed a Monte Carlo simulation. A set of Gold spreading sequences of length $N = 127$ chips and an ideal RAKE receiver having L_D taps are employed. The jth transmitter in NCC-CDMA scheme employs a set of two spreading sequences of length $N, \mathbf{c}_1^j$ and $\mathbf{c}_2^j$, where $\mathbf{c}_2^j$ is a time shifted version of $\mathbf{c}_1^j$, and is approximately orthogonal to $\mathbf{c}_1^j$. This makes the number of distinct (not time shifted version) spreading sequences being used by each user identical for both NCC-CDMA and CCC-CDMA. Figs. 4 and 5 show the the upper-bounds on bit-error rate (BER) and the Monte Carlo simulated BER versus $\bar{E}_b/N_0$, where $\bar{E}_b/N_0 = \sum_{l=0}^{L_D-1} \sigma_l^2 E_b/N_0$ is the average SNR. We can see that the proposed scheme

TABLE III
L, d_p^2, AND d_{free}^2 FOR TWO CC-CDMA SCHEMES

code rate(r)	memory size(v)	CCC-CDMA			NCC-CDMA		
		L	d_p^2	d_{free}^2	L	d_p^2	d_{free}^2
$\frac{1}{2}$	2	5	4^5	20	6	4^5	20
	3	6	4^6	24	8	4^6	24
	4	7	4^7	28	10	4^7	28
	5	8	4^8	32	12	4^8	32
$\frac{1}{4}$	2	10	4^{10}	40	12	4^{10}	40
	3	13	4^{13}	52	16	4^{13}	52
	4	16	4^{16}	64	20	4^{16}	64
	5	18	4^{18}	72	24	4^{18}	72
$\frac{1}{8}$	2	21	4^{21}	84	24	4^{21}	84
	3	26	4^{26}	104	32	4^{26}	104
	4	32	4^{32}	128	40	4^{32}	128
	5	36	4^{36}	144	48	4^{36}	144

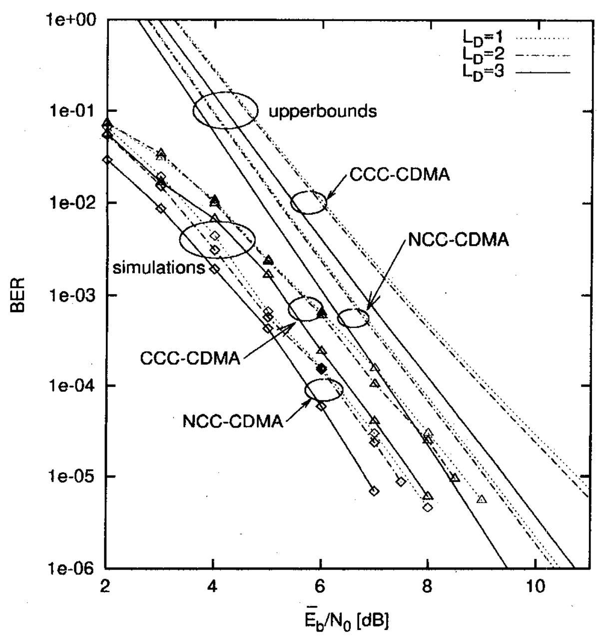

Fig. 4. BER's versus $\bar{E}_b/N_0$ for CCC-CDMA and NCC-CDMA schemes with several values of L_D: $r = 1/2, v = 5, N = 127, K = 10$.

outperforms the conventional CDMA scheme. The Monte Carlo simulations show that an improvement of 1.0–1.3 dB can be attained at $P_b = 10^{-5}$ for v between five and seven and L_D between one and three, and even a higher improvement can be achieved as the required BER is decreased. Notice that for frequency-nonselective Rayleigh-fading channel, which corresponds to $L_D = 1$ case, the performance improvememt is 1.3 dB at $P_b = 10^{-5}$ for v between five and seven. We found that the performance improvement calculated from the upper bound is about 0.1–0.3 dB higher than simulations.

Fig. 6 shows the upper-bounds on BER versus the number of active transmitters, K, for several values of $\bar{E}_b/N_0$. It can be observed that the NCC-CDMA scheme is able to accommodate 56% more users (39 users) than the CCC-CDMA scheme (25 users) for $\bar{E}_b/N_0 = 9$ dB and $P_b = 10^{-5}$,

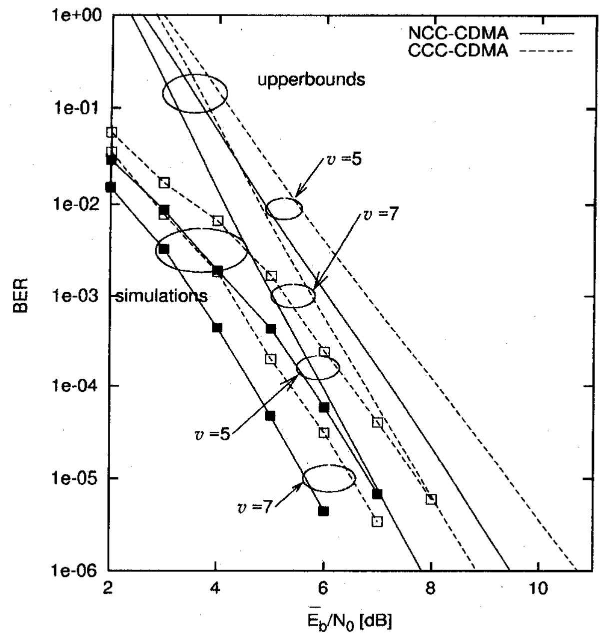

Fig. 5. BER's versus $\bar{E}_b/N_0$ for CCC-CDMA and NCC-CDMA schemes with several values of memory size v: $r = 1/2, L_D = 3, N = 127, K = 10$.

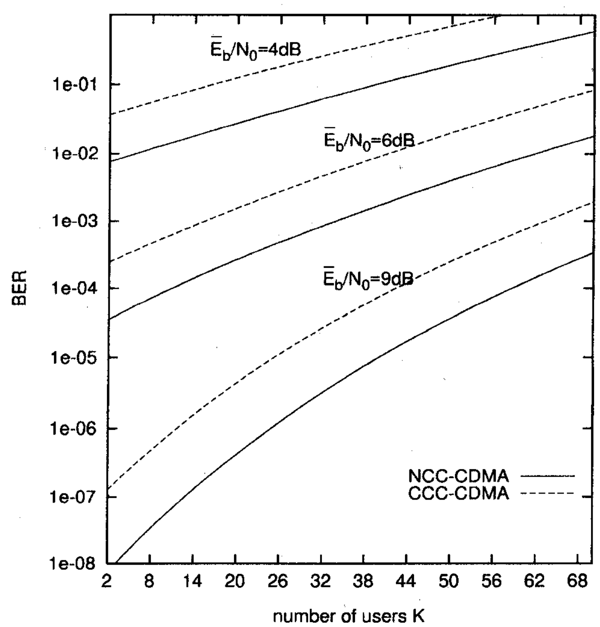

Fig. 6. BER's versus the number of users K for CCC-CDMA and NCC-CDMA schemes with several $\bar{E}_b/N_0$'s: $r = 1/2, v = 7, L_D = 3, N = 127$.

and a similar improvement in capacity can be attained for other BER requirements.

V. CONCLUSION

We found that the asymptotic BEP of the convolutionally coded CDMA system depends on the length of the shortest error event path and the product of symbol distances along that path. Based on this observation, we have proposed a new spreading scheme that maximizes the length of the shortest error event path.

It is found that the new spreading scheme yields an improvement of 1.0–1.3 dB at $P_b = 10^{-5}$ over the conventional CDMA scheme, and even a higher improvement can be achieved as the required BEP is decreased. Furthermore, the new spreading scheme is able to accommodate 56% more users than the conventional CDMA scheme at $P_b = 10^{-5}$ for code rate $r = 1/2$, encoder memory size $v = 7$, and $\bar{E}_b/N_0 = 9$ dB.

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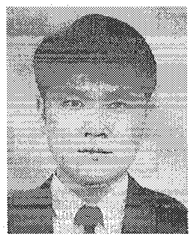

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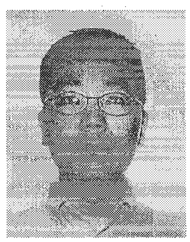

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